



## Redshift Properties of MASIV sources

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**Abstract.** The MASIV 5 GHz VLA flat-spectrum radio source variability survey of the northern sky has discovered that more than half of its 475 targets exhibited interstellar scintillation (ISS) at one or more of the four survey epochs. We present the first results of the spectroscopic identifications of the sample. For 253 sources the spectroscopic identification is obtained and evaluated from the literature. For 76 sources in the RA range  $13^h$ – $24^h$  we use data from our own observations with the Nordic Optical Telescope and the Palomar Hale Telescope. Based on their optical spectrum and luminosity, the majority of the sources are QSOs. However there are many BL Lac objects and some narrow line/weak AGN in the sample. The BL Lac fraction appears to be much higher amongst the ISS than non-ISS sources and most other type of AGN than BL Lac or FSRQ are non-ISS sources, which indicates a higher incidence of bright, compact cores in BL Lacs. Our results show that ISS sources have a flat redshift distribution in comparison to the non-ISS sources. Particularly intriguing is a lack of  $z > 2$  ISS sources in the MASIV sample, which may be explained by the scattering properties of the Intergalactic Medium. The radio and optical luminosities of ISS and non-ISS sources are similar. Finally, we find that about 50% of the ISS sources with  $S_{5\text{ GHz}} > 0.3\text{ Jy}$  are LAT-detected in comparison to a 25% detection rate of the non-ISS sources.

### 1. Introduction

There is now considerable evidence that Short-Timescale Variability (STV) results primarily from scintillation in the turbulent ionized interstellar medium of our Galaxy. This conclusion emerges from two lines of observational evidence. Time delays have been detected between the arrival times of the intensity fluctuations from STV sources at two widely-spaced telescopes (e.g. Bignall et al. 2006). Further, annual cycles have been detected in the timescale of STV sources (Jauncey et al. 2003), a periodic modulation that most plausibly results from the change in the relative velocity of the Earth and the scattering medium through the course of a year. Though questions remain (Jauncey et al. 2001 & Krichbaum et al. 2002), interstellar scintillation is the only reasonable explanation of these observations.

Though an extrinsic (as opposed to intrinsic) origin for STV points to less extreme physical conditions for the sources that exhibit this phenomenon, scintillators are still among the most extreme and active radio AGN known. For a source to scintillate its angular size must be comparable to that of the first Fresnel zone (Narayan 1992) which implies microarcsecond angular sizes for screen distances of tens to hundreds of parsecs. Further, brightness

temperatures of some scintillators are well in excess of  $10^{14}\text{ K}$  (Macquart 2000) which implies Doppler factors of several hundred or more (Readhead 1994) which is significantly higher than seen in VLBI surveys (e.g., Zensus et al. 2003). Thus, an investigation of the properties of AGN that exhibit STV is of considerable astrophysical interest.

In order to construct a large sample of scintillating extragalactic sources with which to examine microarcsecond structure, parent population and the spatial distribution of scintillators, and to probe the turbulent ISM responsible for the scintillation, the Microarcsecond Scintillation-Induced Variability (MASIV) survey was undertaken (Lovell et al. 2003).

### 2. The sample

The MASIV sample has its roots in two radio catalogues CLASS (Cosmic Lens All Sky Survey; Myers et al. 1995) and JVAS (Jodrell Bank VLA Astrometric Survey; e.g., Wilkinson et al. 1998). Compact sources, unresolved at 8.4 GHz with the VLA, and having a flat-spectrum (CLASS/JVAS vs NVSS catalog (NRAO VLA Sky Survey; Condon et al. 1998) with a spectral index lower limit of  $-0.3$  ( $S \propto \nu^\alpha$ ) were chosen. The sample was next reduced into strong ( $S_{8.4\text{ GHz}} > 0.6\text{ Jy}$ ) and weak

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subsamples ( $S_{8.4\text{GHz}} < 0.13\text{Jy}$ ) of about 300 sources each. Finally, the sources were selected to have uniform sky distribution in order to have the best possible coverage for the Very Large Array (VLA) at 5 GHz observations (see Lovell et al. 2003 for details). After removing sources with the presence of structure or confusion we are left with the final sample of 475 point sources common to all four epochs of MASIV observations. Lovell et al. (2008) presented the statistical analysis of the VLA data and found that the STV properties are consistent with the ISS. About 43% of the sources were variable in more than two epochs. The majority of the scintillators appear to be “episodic” (varying only in some epochs) rather than “persistent” (varying at all epochs) and “Rapid” scintillators with short intra-hour timescales are remarkably rare. For the analysis below, we compare the optical and radio properties to the STV. Following Lovell et al. (2008), we label sources which show STV in ‘X’ epochs, ‘STVX’ where ‘X’ is zero for non-STV sources and 1, 2, 3 or 4 for source that met the MASIV variability criteria for one, two, three or all four epochs and finally sources with two or more time showing STV are grouped as ISS-sources.

### 3. Optical data

The main goal of this work is to present the spectroscopic identifications and redshifts of the MASIV sample. The majority of the radio strong sample sources have observed spectroscopically and the results collected in NED (68%). However this is not the case with the weak sample (22%). In order to define the sample for optical spectroscopy and select appropriate observing resources accurate optical identification was a prerequisite.

For optical identification we used mainly the Sloan Digital Sky Survey (SDSS DR 5 Adelman-McCarthy et al. 2007) and GSC 2.3 (Lasker et al. 2008). 165 sources were identified from the SDSS DR5, which is complete down to  $r=22.5$  ( $\lambda_{\text{eff}} \sim 6230\text{\AA}$ ) with astrometric accuracy about  $0''.1$  (Pier et al. 2003) and covers  $\sim 8000$  square degrees, essentially the Galactic gap and some smaller patches. For 223 sources we used GSC 2.3 which is scans of the POSS-II plates, and have  $F$  magnitudes ( $\lambda_{\text{eff}} \sim 6500\text{\AA}$ ) down to 20.5 with poorer photometric ( $\sim 0.15$  mag) and astrometric accuracy ( $0''.3$ ) than the SDSS.

The new redshift were obtained using the 2.56m Nordic Optical Telescope (NOT) which is located at La Palma and the 5m Palomar Hale Telescope. Most of the NOT data was obtained during two observing runs (July 2005 and July 2006) supplemented by a few additional nights. The Hale data was obtained during an observing run on August 2007. At NOT, low resolution (dispersion of  $3\text{\AA}/\text{pixel}$ ) spectra were obtained using ALFOSC with grism 4 with practical wavelength coverage about  $3800 - 8000\text{\AA}$ . At Hale, the Double Spectrograph (DBSP) was used with continuous wavelength coverage from  $\sim 3400$  to  $9500\text{\AA}$ , with dispersion of  $\sim 1\text{\AA}$  and  $\sim 4.9\text{\AA}$  per pixel for blue and red arms respectively.

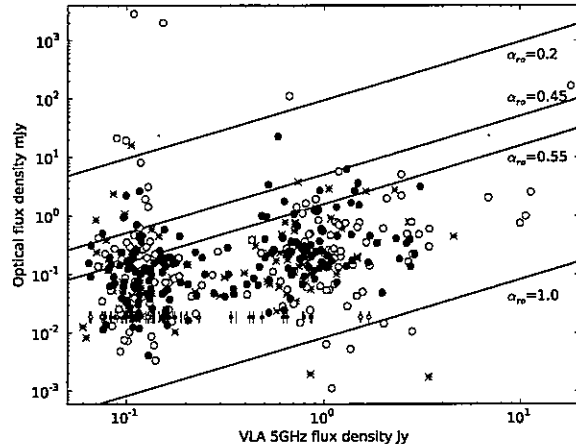


Fig. 1. VLA versus galactic extinction corrected R-band flux density. The diagonal lines indicate constant radio-optical flux ratio where open symbols are non-ISS sources, crosses STV1 and filled ISS sources. The vertical line indicates upper limit.

The redshifts were determined from the narrow emission lines whenever possible or, in most cases, broad emission lines. On the basis of the optical spectrum the sources have been divided into three main groups: weak line objects (mainly BL Lacs), objects with strong and broad lines (mainly FSRQ) and objects with strong and narrow lines (mainly Seyfert 2’s). Our spectroscopic classification scheme is adapted from previous works e.g., Caccianiga et al. (2002a).

### 4. Results, Sample properties

The optical identification rate is 86% (215) for the radio “strong” and 77% (197) for the “weak” sample. The apparent magnitudes are similar amongst the STV-groups and there is no evidence of an STV apparent optical brightness correlation. Figure 1 shows the optical versus radio flux density with diagonal lines indicating constant radio-optical flux ratio, suggesting that the “weak” sample has a broader range of SEDs than the “strong” one.

We have measured 70 new redshifts with spectroscopic identification and 6 new featureless spectrum BL Lacs from our own observations. In addition we include 232 redshifts and 21 BL Lac objects from the literature. The majority (79%, 261) of the sources have broad emission lines (FSRQs, some Sy1s) the next largest group is BL Lac objects (15%, 48) and the remaining 6% (20) are low luminosity AGNs (Sy2, PEG, LINER) and galaxies. There is only little difference in the spectroscopic identification between the radio “strong” and “weak” samples. At redshift  $z < 0.2$ , most of the “strong” sample objects are BL Lacs or have broad emission lines in contrast to the “weak” sample, where most low- $z$  objects have narrow emission lines or “galaxy” type of spectrum. Interestingly, only one of the ISS sources has a narrow emission line spectrum, all the others have broad or no emission lines.

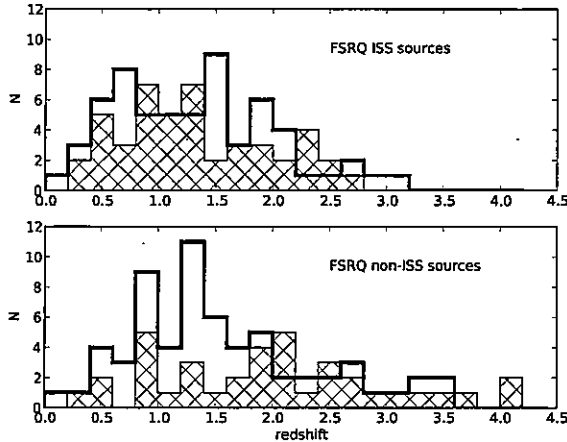


Fig. 2. Redshift distributions of the FSRQs. The open histogram shows the radio “strong” and hatched “weak” sample.

There are 71 *Fermi*/LAT detected sources of which 65 have  $S_{5\text{GHz}} > 0.3\text{Jy}$ . The LAT detection rate of the radio “strong” ISS sources is higher than the non-ISS sources (38% vs 21%), however for the BL Lac-FSRQ fractions are similar between the full and ISS samples. Of the BL Lac objects 10% showed no STV, 70% are ISS-sources and of the featureless spectrum sources  $\sim 50\%$  are STV4 sources. The fraction of BL Lacs increases from 6% of the non-variable to 40% of the STV4 sources and this is seen in both “strong” and “weak” samples. Finally, only  $\sim 40\%$  of the BL Lacs have emission line redshift.

The median redshift of the full sample has only a modest increase from “strong” to “weak” sources (1.23 and 1.29). However the redshift distribution depends on the spectroscopic identification of the object, radio flux limit and the STV properties. The median redshift of the radio “strong” FSRQ sample is only slightly lower than that of the radio “weak” (1.33 vs 1.46). These values are similar to the mean redshifts from previous studies e.g., FSRQs from 1 J, S4 and DXRBS samples (Landt et al 2001).

Inspecting the redshift distributions and the STV properties (Figure 2) it appears that the distributions of the variable and non-variable are different. The radio “strong” sample has similar median redshifts for ISS and non-ISS sources ( $z_{\text{med}} = 1.30$  vs  $1.36$ ), however this is not the case for radio “weak” sample ( $z_{\text{med}} = 1.24$  vs  $1.94$ ). The Kolmogorov-Smirnov test suggests that there is a 0.5% chance that the radio “weak” FSRQ ISS and non-ISS samples are drawn from the same parent population.

In Figure 3 we plot the optical and radio luminosities. FSRQ have  $P_r = 10^{25.4-29}$  W/Hz, BL Lac objects and Seyfert 1/2 type have  $P_r$  between  $10^{25-27}$  W/Hz and and PEG, galaxy, Liner type objects are weaker than  $10^{25}$  W/Hz. The absolute magnitude range from -22 to -30 for the FSRQs and between -20 to -26 for the rest of the objects. At similar redshift ISS and non-ISS FSRQs have similar radio power and optical luminosity with Kolmogorov-Smirnov and Student’s *t*-test indicating that the two sam-

ples are drawn from the same parent population. The source distributions are overlapping with an apparent radio power optical luminosity correlation. However, the apparent correlation is much weaker when selecting only redshift 1.0-2.0 FSRQs (Figure 3), when the slope is -1.2 with Pearson correlation coefficient of -0.49 with high statistical significance. This suggests that correlation between radio and optical luminosities is mild at best.

## 5. Discussion

Fossati et al. (1998) found for blazars a tight correlation between optical and radio luminosity and also that the SED is a function of radio power. This, so called ‘blazar sequence’, predicts that low radio power sources have higher SED peak frequency than a high radio power source, due to radiative cooling. The low radio power sources should have their SED peak at X-rays and high power sources at infrared. The correlation has been disputed (see a review e.g., Padovani (2007a), but see also the revised model by Ghisellini & Tavecchio (2008)). We found only weak correlation between the radio power and optical luminosities, when reducing the selection effects such as the object, redshift-luminosity correlation and *k*-correction effects.

We found about the same fraction of FSRQs, BL Lacs and AGNs as has been found from Candidate Gamma-Ray Blazar Survey (CGRaBS, Healey et al. 2008) and Deep X-Ray Radio Blazar Survey (DXRBS, Padovani et al. 2007b). By the selection, “The CLASS blazar survey” (CBS, Marcha et al 2001, Caccianiga et al 2002a) is closest to MASIV however it also has weak ( $S_{8.6\text{GHz}} \sim 1\text{mJy}$ ), but only optically bright ( $R \leq 17.5$ ) sources. This results more low redshift ( $z < 0.15$ ) and narrow-line sources than the MASIV survey. Also, optically less luminous but powerful radio sources (Figure 3, where  $M_R > -23$  and  $\text{Log} P > 26$ ) are missing from the CBS.

It is interesting to note that STV4 is one of the most effective preselection to find BL Lac objects. In comparison, radio-X-ray selection results 18-25% BL Lacs (DXRBS Padovani et al. 2007b and XB-REX, Caccianiga, et al. 2002b) however, 50% of the  $\gamma$ -ray selected blazars are BL Lacs (Abdo et al. 2010).

Our results suggest that the selection criteria of persistent STV strongly favours BL Lac objects as 43% of the sources showing STV in all four epochs are BL Lac objects. The compact radio structure seems to give similar source distribution as radio/X-ray selection. However there are fewer low radio power objects and the number of objects with featureless optical spectrum is greater amongst compact radio core objects. Also compact radio structure removes mainly Type 2 objects and favours FSRQs and rejects low redshift sources. Similarly having fainter magnitude limit the fraction of FSRQs increases and Type 2 decreases. However this might be due to the fact at fainter magnitudes FSRQs with strong emission lines are easier to identify than BL Lacs and Type 2 targets with weak or no emission lines.

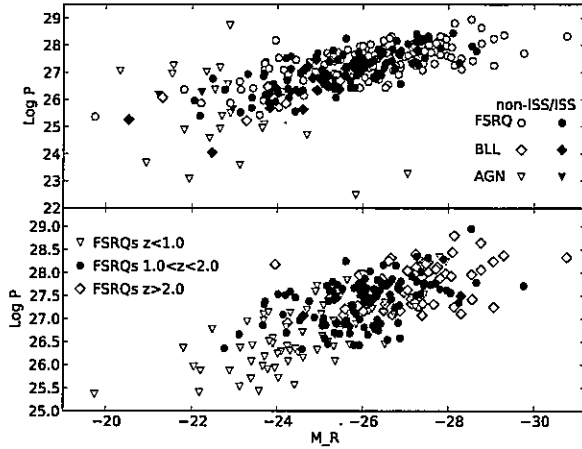


Fig. 3. Absolute optical R-magnitude vs radio power. The circles indicate FSRQs, stars BL Lac objects and triangles Type 2 objects and galaxies. In the top panel filled symbol indicates ISS source and open non-ISS sources. The bottom panel shows different redshift ranges for FSRQs.

Lovell et al. (2008) found that at redshift 2 the number of ISS sources decreases. Using the present data with spectroscopic identifications the trend has been confirmed for the FSRQs with high statistical level. In addition, we found that at similar redshift ISS and non-ISS sources have similar radio and optical luminosities. This suggests that the two type sources are similar and we argue that the difference is extrinsic to the source rather than intrinsic.

Based on 1043  $\gamma$ -ray sources Abdo et al. (2010) found among other things, that most 1LAC sources are blazars, the redshift distributions of the 1LAC FSRQs peak at  $z \sim 1$  with maximum redshift  $z = 3.1$  and that about 50% of the 1LAC blazars are BL Lac objects. These properties are surprisingly close to the MASIV ISS sources, where all but one of the ISS sources have broad/no lines, the redshift distributions of the ISS sources are similar for the 'strong' and 'weak' radio sources with  $z_{\text{median}} = 1.2$  and  $z_{\text{max}} = 3.1$  and the fraction of BL Lacs increases with the STV so that 40% of STV4 sources are BL Lacs.

Our results are consistent with previous study of the STV properties with the Pearson-Readhead compact extragalactic radio sources (Lister et al 2001) if the BL Lac objects and FSRQs are studied as one sample. They have found that STV sources have smaller emission line widths and lower 5GHz luminosities than the non-STV sources. Finally, we note that although MASIV sources probe finer scales than e.g., VLBI, our "resolution" for the most nearby ISS source (Mkn 421) is about  $\sim 7 \times 10^{16}$  cm, more than hundred times the estimate of the size of an X-ray emission region.

## 6. Summary

We have presented the optical and spectroscopic identification of a new sample of 475 compact flat spectrum radio

sources. About half of these sources show STV. We have spectroscopic identifications and redshifts for 329 source, comprising  $\sim 90\%$  the radio "strong" ( $S_{5\text{GHz}} > 0.3$  Jy) and 50% complete radio "weak" sample ( $0.3 < S_{5\text{GHz}} < 0.06$  Jy).

- About 80% of the "strong" and 60% of the "weak" sources have an optical counter part with  $R < 20$  magnitude.

- Almost 80% of the MASIV sources are identified as FSRQs,  $\sim 13\%$  BL Lacs and  $\sim 7\%$  narrow-line objects or galaxies. The spectroscopic identifications are similar for radio "strong" and "weak" samples. Our results suggest that the compact radio structure favours FSRQs and BL Lacs amongst flat spectrum sources.

- Of the ISS sources 25% are BL Lacs, and the rest are almost exclusively FSRQs. The fraction of BL Lacs increases with the STV and 40% of the persistent STV sources are BL Lac objects.

- Radio and optical luminosities of the ISS and non-ISS FSRQs are similar at a given redshift, suggesting intrinsically similar SEDs.

- The redshift distribution of the ISS FSRQs appears to be independent of the radio flux in contrast to the non-ISS. Taking into account similar luminosities this suggests that lack of high redshift ISS sources is related to the environment of the source rather than being intrinsic.

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